



INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification: H04B 10/04, G02B 6/10, H04B 10/16	A1	(11) International Publication Number: WO 00/27054 (43) International Publication Date: 11 May 2000 (11.05.2000)
(21) International Application Number: PCT/US99/25885 (22) International Filing Date: 04 November 1999 (04.11.1999) (30) Priority Data: 09/185,820 04 November 1998 (04.11.1998) US (60) Parent Application or Grant CORVIS CORPORATION [/]; (). PRICE, Alistair, J. [/]; ().	Published	
<p>(54) Title: OPTICAL TRANSMISSION APPARATUSES, METHODS, AND SYSTEMS (54) Titre: PROCÉDÉS, APPAREILS ET SYSTEMES DE TRANSMISSION OPTIQUE</p> <p>(57) Abstract</p> <p>Apparatuses, methods, and systems are disclosed that provide for simultaneously upconverting electrical signals (λ_{e1}, λ_{en}) carrying information at electric frequencies onto optical subcarrier lightwave frequencies (ν_0) that are greater and less than the carrier frequency of the lightwave onto which the electrical frequencies were upconverted. The upconversion of the electrical signals can be performed with or without suppression of the optical carrier frequency.</p> <p>(57) Abrégé</p> <p>L'invention concerne des procédés, des appareils et des systèmes permettant de transposer simultanément, par montée en fréquence, des signaux électriques (λ_{e1}, λ_{en}) portant des informations de fréquence électrique, sur des fréquences (ν_0) d'onde lumineuse de sous-porteuse optique supérieures ou inférieures à la fréquence de porteuse sur laquelle la montée en fréquence des signaux électriques peut s'effectuer. La montée en fréquence des signaux électriques peut s'effectuer avec ou sans suppression de la fréquence de porteuse optique.</p>		

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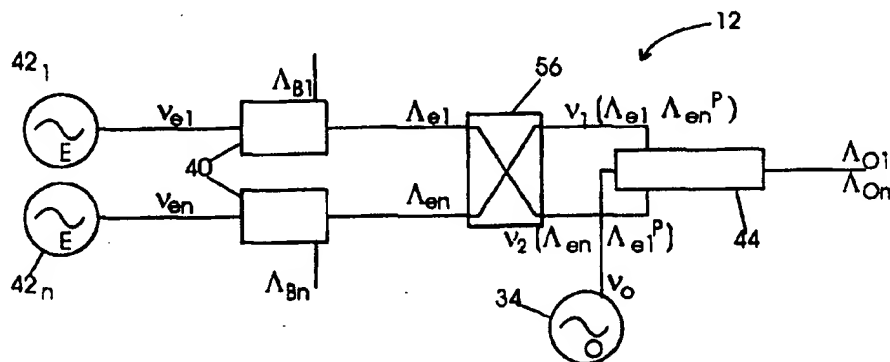
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(51) International Patent Classification 6 : H04B 10/04, 10/16, G02B 6/10		A1	(11) International Publication Number: WO 00/27054
			(43) International Publication Date: 11 May 2000 (11.05.00)
(21) International Application Number: PCT/US99/25885		(81) Designated States: BR, CA, CN, IN, JP, MX, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).	
(22) International Filing Date: 4 November 1999 (04.11.99)			
(30) Priority Data: 09/185,820 4 November 1998 (04.11.98) US		Published With international search report. Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.	
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(54) Title: OPTICAL TRANSMISSION APPARATUSES, METHODS, AND SYSTEMS



(57) Abstract

Apparatuses, methods, and systems are disclosed that provide for simultaneously upconverting electrical signals (λ_{e1} , λ_{en}) carrying information at electric frequencies onto optical subcarrier lightwave frequencies (ν_0) that are greater and less than the carrier frequency of the lightwave onto which the electrical frequencies were upconverted. The upconversion of the electrical signals can be performed with or without suppression of the optical carrier frequency.

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Description

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OPTICAL TRANSMISSION APPARATUSES, METHODS, AND SYSTEMS

FIELD OF THE INVENTION

The present invention is directed generally to the transmission of information in communication systems. More particularly, the invention relates to transmitting information via optical signals in optical transmission systems and transmitters for use therein. This application claims the benefit of U.S. Patent Application No. 09/185,820 filed November 4, 1998. This application also is related to commonly assigned U.S. patent application Serial Nos. 09/185,821 and 09/185,816, filed on November 4, 1998, which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

The development of digital technology provided resources to store and process vast amounts of information. While this development greatly increased information processing capabilities, it was soon recognized that in order to make effective use of information resources, it was necessary to interconnect and allow communication between information resources. Efficient access to information resources requires the continued development of information transmission systems to facilitate the sharing of information between resources.

The continued advances in information storage and processing technology has fueled a corresponding advance in information transmission technology. Information transmission technology is directed toward providing high speed, high capacity connections between information resources. One effort to achieve higher transmission capacities has focused on the development of optical transmission systems for use in conjunction with high speed electronic transmission systems. Optical transmission systems employ optical fiber networks to provide high capacity, low error rate transmission of information over long distances at a relatively low cost.

5 The transmission of information over fiber optic
networks is performed by imparting the information in some
manner to a lightwave carrier by varying the characteristics
of the lightwave. The lightwave is launched into the
10 5 optical fiber in the network to a receiver at a destination
for the information. At the receiver, a photodetector is
used to detect the lightwave variations and convert the
information carried by the variations into electrical form.

15 In most optical transmission systems, the information
10 is imparted by using the information data stream to either
modulate a lightwave source to produce a modulated lightwave
or to modulate the lightwave after it is emitted from the
light source. The former modulation technique is known as
20 "direct modulation", whereas the latter is known as
15 "external modulation", i.e., external to the lightwave
source. External modulation is more often used for higher
speed transmission systems, because the high speed direct
modulation of a source often causes undesirable variations
25 in the wavelength of the source. The wavelength variations,
known as chirp, can result in transmission and detection
20 errors in an optical system.

30 Data streams can be modulated onto the lightwave using
a number of different schemes. The two most common schemes
are return to zero (RZ) and non-return to zero (NRZ). In RZ
25 modulation, the modulation of each bit of information begins
and ends at the same modulation level, i.e., zero, as shown
in Fig. 1a. In NRZ schemes, the modulation level is not
returned to a base modulation level, i.e., zero, at the end
of a bit, but is directly adjusted to a level necessary to
40 30 modulate the next information bit as shown in Fig. 1b.
Other modulation schemes, such as duobinary and PSK, encode
the data in a waveform, such as in Fig. 1c, prior to
modulation onto a carrier.

45 In many systems, the information data stream is
35 modulated onto the lightwave at a carrier wavelength, λ_0 ,
(Fig. 2a) to produce an optical signal carrying data at the
carrier wavelength, similar to that shown in Fig. 2b. The

5 modulation of the carrier wavelength also produces symmetric
lobes, or sidebands, that broaden the overall bandwidth of
the optical signal. The bandwidth of an optical signal
determines how closely spaced successive optical signals can
10 be spaced within a range of wavelengths.

Alternatively, the information can be modulated onto a
wavelength proximate to the carrier wavelength using
subcarrier modulation ("SCM"). SCM techniques, such as
15 those described in U.S. Patent Nos. 4,989,200, 5,432,632,
and 5,596,436, generally produce a modulated optical signal
in the form of two mirror image sidebands at wavelengths
symmetrically disposed around the carrier wavelength (Fig.
2c). Generally, only one of the mirror images is required
20 to carry the signal and the other image is a source of
signal noise that also consumes wavelength bandwidth that
would normally be available to carry information.
Similarly, the carrier wavelength, which does not carry the
25 information, can be a source of noise that interferes with
the subcarrier signal. Modified SCM techniques have been
developed to eliminate one of the mirror images and the
30 carrier wavelength, such as described in U.S. Patent Nos.
5,101,450 and 5,301,058.

Initially, single wavelength lightwave carriers were
spatially separated by placing each carrier on a different
35 fiber to provide space division multiplexing ("SDM") of the
information in optical systems. As the demand for capacity
grew, increasing numbers of information data streams were
spaced in time, or time division multiplexed ("TDM"), on the
single wavelength carrier in the SDM system as a means to
40 provide additional capacity. The continued growth in
transmission capacity has spawned the transmission of
multiple wavelength carriers on a single fiber using
wavelength division multiplexing ("WDM"). In WDM systems,
45 further increases in transmission capacity can be achieved
not only by increasing the transmission rate of the
35 information via each wavelength, but also by increasing the
number of wavelengths, or channel count, in the system.

5 There are two general options for increasing the
channel count in WDM systems. The first option is to widen
the transmission bandwidth to add more channels at current
10 channel spacings. The second option is to decrease the
5 spacing between the channels to provide a greater number of
channels within a given transmission bandwidth. The first
option currently provides only limited benefit, because most
optical systems use erbium doped fiber amplifiers ("EDFAs")
15 to amplify the optical signal during transmission. EDFAs
have a limited bandwidth of operation and suffer from non-
20 linear amplifier characteristics within the bandwidth.
Difficulties with the second option include controlling
optical sources that are closely spaced to prevent
interference from wavelength drift and nonlinear
15 interactions between the signals.

A further difficulty in WDM systems is that chromatic
25 dispersion, which results from differences in the speed at
which different wavelengths travel in optical fiber, can
also degrade the optical signal. Chromatic dispersion is
20 generally controlled in a system using one or more of three
techniques. One technique to offset the dispersion of the
30 different wavelengths in the transmission fiber through the
use of optical components such as Bragg gratings or arrayed
waveguides that vary the relative optical paths of the
35 wavelengths. Another technique is intersperse different
types of fibers that have opposite dispersion
characteristics to that of the transmission fiber. A third
40 technique is to attempt to offset the dispersion by
prechirping the frequency or modulating the phase of the
30 laser or lightwave in addition to modulating the data onto
the lightwave. For example, see U.S. Patent Nos. 5,555,118,
5,778,128, 5,781,673 or 5,787,211. These techniques require
45 that additional components be added to the system and/or the
use of specialty optical fiber that has to be specifically
35 tailored to each length of transmission fiber in the system.

New fiber designs have been developed that
substantially reduce the chromatic dispersion of WDM signals
50 during transmission in the 1550 nm wavelength range.

5 However, the decreased dispersion of the optical signal
allows for increased nonlinear interaction, such as four
wave mixing, to occur between the wavelengths that increases
signal degradation. The effect of lower dispersion on
10 5. nonlinear signal degradation becomes more pronounced at
increased bit transmission rates.

The many difficulties associated with increasing the
number of wavelength channels in WDM systems, as well as
15 increasing the transmission bit rate have slowed the
continued advance in communications transmission capacity.
10 In view of these difficulties, there is a clear need for
transmission techniques and systems that provide for higher
capacity, longer distance optical communication systems.
20

BRIEF SUMMARY OF THE INVENTION

15 Apparatuses and methods of the present invention
address the above need by providing optical communication
25 systems that include transmitters that can provide for
pluralities of information carrying wavelengths per optical
transmission source, dispersion compensation, and/or
20 nonlinear management in the system. In an embodiment, the
information data stream is electrically distorted to
30 compensate for chromatic dispersion of a lightwave/optical
signal during transmission. The electrical distortion can
be used to compensate for negative or positive dispersion in
35 varying amounts depending upon the characteristics of the
25 optical fiber in the network and to some extent offset
nonlinear interactions that produce distortion of the
optical signal. Electrical distortion can be specifically
40 tailored to each wavelength and bit rate used in the optical
30 system.

Electrical dispersion compensation can be used in
conjunction with other methods, such as dispersion
45 compensating fiber or time delay components to control the
level of dispersion at various points in the network. The
35 amount of dispersion in the system can be controlled to
provide a substantially predetermined value of net
50 dispersion, e.g., zero, at the end of a link, to provide an

5 average value over the link, and/or to minimize the absolute dispersion at any point in the link.

Electrical distortion compensation can be used with RZ, NRZ, ASK, FSK, PSK, and duobinary formats, as well as other modulation formats and baseband and subcarrier modulation techniques. In addition, the amount of electronic distortion applied to a signal can be controlled via a feedback loop from a receiver in the system to allow fine tuning of the compensation. In this manner, changes in the network performance with time can be accommodated.

10 In an embodiment, an information data stream is modulated on to an electrical carrier, such radio frequency ("RF") or microwave carrier, frequency ν_e . The modulated electrical carrier is upconverted on to a lightwave carrier having a wavelength λ_0 and frequency ν_0 produced by the optical transmission source to produce an information carrying lightwave at wavelength λ_1 and frequency ν_{0e} . The upconverter can be used to simultaneously upconvert a plurality of electrical frequencies onto different subcarrier lightwaves. In an embodiment, the information is modulated onto the electrical carrier in duobinary format, which provides for more narrow subcarrier bandwidths.

15 In an embodiment, the lightwave carrier from the optical source is split into a plurality of split lightwave carriers, each of which has one or more data streams upconverted or modulated onto it. The subcarrier lightwave optical signals generated from the split lightwave optical carriers are then recombined into the optical signal for transmission. The split lightwave carrier overcomes the problem of maintaining close wavelength spacing between multiple carriers in an operating system by employing a common optical source. The optical source providing the lightwave carrier may include one or more lasers or other optical sources.

20 The split lightwave carrier also provides a method of placing multiple information carrying wavelengths near the lightwave carrier without having to upconvert or modulate

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5 more than one data stream at a time onto a lightwave
carrier. The upconverted lightwaves can be at wavelengths
that are greater and/or less than the carrier wavelength and
10 symmetrically or asymmetrically positioned relative to the
5 carrier wavelength. In addition, subcarriers can be
simultaneously upconverted onto the same lightwave, at least
one subcarrier with a higher frequency and at least one
subcarrier with a lower frequency than the carrier
15 frequency.

10 The upconversion of the modulated electrical carrier
can be performed using double or single sideband
upconverters with or without suppression of the carrier
20 wavelength λ_0 . However, the reduction or elimination of the
carrier wavelength λ_0 and any mirror image sideband will
15 eliminate unwanted signals that could interfere with the
upconverted signal.

25 In an embodiment, a two sided, single sideband
upconverter is provided to modulate multiple information
data streams onto both longer and shorter wavelengths. In
20 those embodiments, one upconverter can be used to upconvert
data on equally or differently spaced subcarriers relative
30 to the carrier wavelength.

35 In an embodiment, the polarization of adjacent
lightwave carriers is controlled to decrease the nonlinear
25 interactions of the signals. For example, adjacent
wavelength signal can be orthogonally polarized to decrease
the extent of four wave mixing that occurs between the
signals during transmission. In addition, the wavelength
40 spacing between neighboring upconverted signals can be
30 selected to lessen non-linear interaction effects.

45 Accordingly, the present invention addresses the
aforementioned problems with providing increasing the number
of channels and the transmission performance of optical
systems. These advantages and others will become apparent
35 from the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention will now be described, by way of example only, with reference to the accompanying drawings wherein like members bear like reference numerals and wherein:

Figs. 1a-c show a typical baseband return to zero ("RZ") and non-return to zero ("NRZ") data signal;

Figs. 2a-c show the intensity versus wavelength plots for an unmodulated optical carrier, modulated carrier, and modulated subcarriers of the carrier;

Figs. 3-4 show embodiments of the system of the present invention; and,

Figs. 5 shows an embodiment of a transmitter of the present invention;

Fig. 6a&b show transmission & reception time versus wavelength curves;

Figs. 7a-c show embodiments of signal distorters of the present invention

Figs. 8-11 show embodiments of transmitters of the present invention

Fig. 12 shows an embodiment of transmitters of the invention;

Fig. 13 shows an embodiment of upconverters of the present invention;

Figs. 14-16 show embodiments of transmitters of the present invention; and,

Fig. 17 shows a polarizing element of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

5 The operation of optical systems 10 of the present invention will be described generally with reference to the drawings for the purpose of illustrating present embodiments only and not for purposes of limiting the same. As shown in 10 Fig. 3, the system 10 includes an optical transmitter 12 configured to transmit information, i.e., data, etc., via one or more information carrying optical wavelengths λ_1 to 15 an optical receiver 14 through one or more segments of optical fiber 16j. The system 10 may also include one or 20 more dispersion compensating components 18 and feedback controllers 20, as well as other optical components such as optical amplifiers 22, add/drop devices 24, and the like.

As shown in Fig. 4, the system 10 can be embodied as a 15 network including a plurality of transmitters 12 and receivers 14 in optical communication through one or more 25 optical switches 26, combiners 28, and/or distributors 30. For example, optical and digital cross connect switches and routers, multiplexers, splitters, and demultiplexers can be 20 employed in the system 10. The transmitters 12 and receivers 14 can interface directly with electrical transmission systems or via electrical switches or 30 interfaces to other optical systems that operate using the same or different wavelengths.

35 In an embodiment, the transmitter 12 is configured to electrically distort an electrical signal carrying data to 25 compensate for chromatic dispersion that occurs as an optical signal λ_0 carrying the data is transmitted through 40 the optical fiber 16j. The electronic data signal λ_e can be in a baseband λ_b (i.e., binary, direct current), coded λ_c , 30 or a modulated electrical carrier λ_e format.

45 In an embodiment of the transmitter 12 shown in Fig. 5, an electronic signal distorter 32 is configured to produce a distorted electrical signal λ_{ed} . A distorted optical signal 35 λ_{od} is produced using an electrical to optical converter 33 to impart the the electrical signal λ_{ed} onto an optical 50

5 carrier lightwave λ_0 . The electrical to optical conversion can be performed by upconverting the electrical signal λ_{ED} onto a subcarrier lightwave of an optical carrier lightwave λ_0 provided by an optical source 34. Alternatively, the

10 conversion of electrical signal λ_{ED} can be performed by directly modulating the optical source 34 or externally modulating the optical carrier lightwave λ_0 to produce the optical data signal at the carrier frequency. One or more signal lasers, or other appropriate optical sources as may

15 be known in the art, can be used as the optical source 34.

10 The distortion of the electronic data signal is generally in the form of an electronically induced time delay that varies as a function of the optical wavelength λ_1 in the optical signal λ_0 . The group delay can be used to

15 provide varying amounts of dispersion compensation for each wavelength and for each bit rate in the system 10. The time delay characteristics can be controlled to provide linear and nonlinear, as well as positive, negative, and varying, delay profiles with respect to the wavelength of the signal.

20 Fig. 6a shows an example of a typical relative time delay at the receiver versus wavelength plot for an optical signal being transmitted with zero dispersion at a transmission time t_t . Dispersion of the signal during transmission results in the different wavelengths in the

25 signal reaching the receiver 14 at different times during a reception time interval, Δt_r . The time delay in signal reception is one source of signal distortion that degrades system performance. In the present invention, distorted optical signals can be produced by introducing distortion as

30 a group delay function of frequency, which results in the signal being transmitted over a transmission time interval Δt_t . The electronic distortion is offset by dispersion in the transmission path resulting in the different frequencies reaching the receiver 14 at the same reception time t_r (Fig. 6b), or over a reception time interval of choice (Fig. 6c).

One skilled in the art will appreciate that in the present invention the distortion profile of the electronic data signal can be varied as desired to control the shape of optical signal at the receiver 14. For example, given the interrelation of chromatic dispersion and nonlinear interactions, the electrical distortion characteristics can be shaped to minimize the total distortion at the receiver 14 as opposed to minimizing only the chromatic dispersion. In addition, electronic dispersion compensation can be used in conjunction with dispersion compensating elements 18, such as negative dispersion slope fiber, grating-based elements, etc. as are known in the art.

Figs. 7a-c show embodiments of signal distorter 32 of the present invention. In Fig. 7a, the distorter 32 includes one or more serial electrical circulators 36 having an input to an input port 1 that circulates the electrical signal to an equalizer port 2. A resonator 38 can be connected to port 2 to serve as an all-pass transmission filter that reflects all incident power in a frequency dependent manner back to the port 2, thereby distorting signal. The distorted electrical signal Λ_{ed} exits an output port 3 of the circulator 36 from which it can be passed into another distortion element or exit the signal distorter 32.

An example of resonators 38 that are suitable for use in the present invention are impedance resonators following the general equation:

$$Z(s) = sL + 1/(sC)$$

$$L = RQ/(2\pi f_0)$$

$$C = 1/(4\pi^2 f_0^2 L)$$

$$H(s) = (Z(s) - R)/(Z(s) + R)$$

$$D(\omega) = -d/d\omega(\arg(H(j\omega))), \text{ where}$$

Z = impedance	C = capacitance	D(ω) = group delay
L = inductance	f_0 = frequency	H(s) = equalizer
R = resistance	Q = Q factor	Transfer function

5 One skilled in the art will appreciate that the circulator/resonator embodiments shown in Fig. 7a can be cascaded to provide desired group delay characteristics and that other networks may be used in the present invention.

10 5 For example, in Fig. 7b, the signal distorter 32 includes one or more electrical loop couplers 35 configured to introduce the desired group delay into the electrical carrier signal Λ_e . Various configurations of loop couplers suitable to achieve the desired group delay can be used in the

15 10 distorter 32. Fig. 7c shows an embodiment of the signal distorter 32 for distorting the baseband signal Λ_b . The distorter 32 is used to separate the baseband signal Λ_b into I and Q components by configuring the inductors 37 and capacitors 39 to approximate the following general transfer

20 15 function over the frequency range of interest:

$$|H_I(j\omega)|^2 + |H_Q(j\omega)|^2 = \text{constant}.$$

25 The amount of dispersion in optical fiber 16_i is generally well documented as a function of fiber length and optical wavelength. For example, transmission fiber can

30 20 typically be in the range of 15-20 ps/nm/km in the 1550 nm wavelength range. Thus, the amount of distortion necessary to produce a desired dispersion profile at a point in the optical transmission system can be calculated and adjusted as may be necessary in the system 10. In addition, the

35 25 shape of the distortion profile can be tailored to be linear or nonlinear functions of frequency to compensate for the interrelation of chromatic dispersion and nonlinear interactions.

40 Fig. 8 shows an embodiment of the transmitter 12 in which an electrical modulator 40 is used to modulate the baseband electric signal Λ_b onto an electrical carrier at a frequency ν_c from an electrical carrier source 42. The

45 modulator 40 can be a double balanced mixer as is known in the art. The electrical carrier signal ν_c will be of the

50 35 general form $A(\sin(\omega + \phi))$ and the baseband signal Λ_b of the form $V(t)$ resulting in an output signal of the general form

5 $kV(t)A(\sin(\omega t + \phi_1))$. Thus, if the mean of the baseband signal is zero, the carrier frequency will be suppressed. Likewise, if $V(t)$ has essentially two state $\pm a$, the output will be in PSK format.

10 5 The electrical carrier frequency can be any suitable frequency for the data rate being transmitted, for example, RF or microwave carriers. The signal distorter 32 receives the modulated electrical carrier signal Λ_e at frequency ν_e and provides the distorted electrical carrier signal Λ_{ed} .
15 An upconverter 44 combines the distorted modulated electrical carrier at ν_e with an optical lightwave carrier at a central wavelength λ_0 (frequency ν_0) supplied by an optical source 34. The resulting distorted optical signal Λ_{od} has a frequency $\nu_0 \pm \nu_e$ (" $\nu_{0\pm e}$ ") and central wavelength at
20 $\lambda_{0\pm e}$, which is equal to $c/(\nu_0 \pm \nu_e)$, where c is the speed of light.

25 In embodiments shown in Figs. 8b and 9, the baseband electrical signal Λ_b is provided to the signal distorter 32, which is configured to separate the signal Λ_b into in-phase ("I") and quadrature ("Q") components and distort the
30 20 signal. The IQ components of the distorted electrical signal Λ_{bd} are provided to an IQ modulator 46. In the Fig. 8b embodiments, the I and Q components are modulated onto the electrical carrier ν_e which is upconverted onto the
35 25 optical carrier ν_0 to produce the distorted optical signal Λ_{od} at the central wavelength at $\lambda_{0\pm e}$. In Fig. 9 embodiments, the I and Q components are modulated onto the optical carrier having a central wavelength λ_0 and frequency ν_0 to provide the distorted optical signal Λ_{od} having the
40 30 same central wavelength at λ_0 .

45 Conversely in Fig. 10, the baseband signal Λ_b is modulated onto a portion of the electrical carrier ν_e , which is passed through the signal distorter 32 to produce the distorted electrical signal Λ_{ed} . Another portion of the
50

5 electrical carrier ν_e is provided as input along with the
distorted electrical signal Λ_{ed} to an IQ demodulator 48,
which separates the distorted electrical signal Λ_{ed} into its
IQ components. The IQ components of the electronic signal
10 5 are provided to the IQ modulator 46 which modulates the data
onto the optical carrier at the central wavelength λ_o and
frequency ν_o provided by the optical source 34.

15 In the transmitter 12 of Fig. 11, the electrical
baseband signal Λ_B can be encoded along with a clock signal
10 Λ_{clk} using a data encoder 50 to provide an encoded data
signal Λ_c . The encoded data signal Λ_c may be further passed
through a filter 52, such as a low pass filter, to shape the
20 signal before being passed to the signal distorter 32. In
the transmitter 12 of Fig. 11, the IQ modulator 46 can be
15 used to modulate the distorted electrical signal onto the
electrical carrier frequency ν_e . The electrical carrier can
be amplified using an electrical amplifier 54, split through
25 electrical coupler 56, and upconverted onto the optical
carrier to produce the distorted optical signal Λ_{od} having
30 its center wavelength at λ_{o+e} . One of the controllers 20 in
the system 10 can be used to provide feedback control of the
upconverter 44, as well as the other components such as the
amplifier 54.

35 In embodiments of Fig. 11, the electrical coupler 56 is
25 used to split the signal from each input path between two
output paths and impart a phase shift, i.e. 90° in a 2×2 3dB
coupler, between signals on the respective output paths.
40 The phase shift between the two output paths depends upon
which input path the signal was introduced. Thus, the
30 frequency of the resulting distorted optical signal Λ_{od} will
be either $\nu_{o+e} = \nu_o + \nu_e$ or $\nu_{o-e} = \nu_o - \nu_e$ depending upon which input
45 of the coupler 56 the electrical signals are introduced.

Data encoding techniques, such as duobinary, QPSK, and
others, are useful to decrease the bandwidth of the
35 resulting optical signal. These formats can also affect the

5 extent of distortions that arise from signal dispersion and
non-linear interaction between the signals. The detection
of duobinary and other differential PSK-type signals using
direct detection can be enhanced using an optical filter 58
5 before the receiver 14 in the optical system 10. The
10 optical filter 58 can be matched, i.e., comparably shaped,
to the received optical spectrum of the signal, which can be
controlled in the present invention using the electrical
filter 52. The optical filter 58 can be a Fabry-Perot
15 10 filter or other appropriate filter as may be known in the
art. The electrical filter 52 can be design to account for
and match the properties of the optical filter 58 so as to
minimize the bandwidth of the optical signal. It will be
20 appreciated that the electrical filter 52 can be positioned
15 at different locations within the transmitter 12 and
modified accordingly.

In another aspect of the invention shown in Fig. 12,
25 the transmitter 12 of the present invention can be used to
simultaneously upconvert a plurality of electrical signals
20 Λ_{2n} onto one optical carrier. A plurality of baseband
electrical signals $\Lambda_{21}-\Lambda_{2n}$ are modulated onto a corresponding
30 plurality on electrical carriers provided by sources 42₁-42_n
to provide modulated electrical carriers. Signal distorters
32 can be provided to distort either the baseband signal or
25 the modulated electrical carrier, if dispersion compensation
35 is desired. The modulated electrical carriers are passed
through the electrical coupler 56, which divides the
electrical signals between the two output paths leading to
the upconverter 44.

40 30 Numerous combinations of electrical carriers can be
upconverted using the transmitter configuration of Fig. 12.
For example, electrical sources 42₁ through 42_n can provide
the same or different electrical carrier frequencies and
45 depending upon how the carriers are coupled into the
35 upconverter 44. If more than two electrical carriers are to
be upconverted using the same upconverter 44, the additional
carriers can be combined, or multiplexed, onto the

appropriate coupler input. The resulting optical signal can be produced at longer or shorter wavelengths than the optical carrier wavelength λ_0 as previously discussed. In addition, it may also be possible to use one or more electrical subcarriers to carry additional data along with, or in lieu of, data on the electrical carrier frequency depending upon the electrical subcarrier frequency spacings.

The upconverter 44 in embodiments of Figs. 12 and 13 is configured to upconvert the electrical signal onto a single sideband subcarrier frequency, either ω_{ω_0} or $\omega_{-\omega_0}$, while suppressing the mirror image sideband subcarrier frequency. The upconverter can be operated without or with carrier wavelength suppression, although carrier suppression eliminates unwanted signals that could produce signal interference.

Fig. 14 shows an embodiment of the single side band suppressed carrier upconverter 44 suitable for use in the present invention. Other suitable single side band embodiments include those described by Olshansky in U.S.

Patent Nos. 5,101,450 and 5,301,058, which are incorporated herein by reference. As shown in Fig. 14, the optical

carrier lightwave at frequency ω_0 is split using an optical splitter 60 into two respective optical paths, 62₁ and 62₂, which are further split into optical paths 62₁₁ and 62₁₂.

The split lightwaves in optical paths 62₁ are passed between first upconverter input electrode 64₁ and a pair of ground electrodes 66. Likewise, the split lightwaves in optical paths 62₂ are passed between second upconverter input electrode 64₂ and a pair of ground electrodes 66.

Electrical input signals v_1 and v_2 are provided to the upconverter respective input electrodes 64₁ and 64₂ via first and second inputs, 68₁ and 68₂, respectively. The input signals v_1 and v_2 are upconverted onto the respective split lightwaves passing between the electrodes and combined in cascaded optical combiners 70 to produce the upconverted optical signal λ_0 .

5 In an embodiment, LiNbO_3 is used to form the optical paths 62₁ and 62₂, which can be used to produce linearly polarized optical signals. In addition, bias electrodes can be provided in optical paths 62₁ and 62₂ and/or 62₃ after
10 5 passing through the input electrodes 64₁ and 64₂. The bias electrodes can be used to trim the phase difference of the optical signals upconverted onto the subcarrier lightwaves in each path before the signals are combined.

15 The electrical input signals v_1 and v_2 introduced to the upconverter 44 carrying the same electrical data signal, except that the data signals have a relative phase shift between the first and second inputs, 68₁ and 68₂, according to the relation: $v_1 = v_2 \pm \text{phase shift}$. The sign of the
20 phase shift determines whether the electrical data signal will be upconverted onto lightwave subcarriers that are greater or less than the carrier frequency of the lightwave. Thus, the upconverter 44 can be configured to receive and
25 simultaneously upconvert electrical signals at the same or different electrical frequencies onto different subcarrier lightwave frequencies of the same lightwave by introducing the appropriate phase shift between the electrical input
30 signals. For example, in embodiments of Figs. 12 and 13, 3 dB electrical couplers 56 provide a $\pm 90^\circ$ phase shift, which allows electrical signals to be upconverted onto optical
25 frequencies that are greater or less than the carrier frequency. One skilled in the art will appreciate that other techniques for imparting the phase shift are suitable within the scope of the invention.

40 The transmitter 12 shown Fig. 13 provides a configuration that can be used to symmetrically place two different optical signals around the central wavelength λ_0 of the optical carrier. The electrical carrier 42 supplies the electrical carrier v_c that is split into two paths, each of which is modulated using a corresponding modulator 36₁ or
45 36₂ with electrical baseband signals Λ_{B1} and Λ_{B2} , respectively. The two signals are passed through the electrical coupler 56 which splits and couples the signals
50

5 from each of the two coupler input paths to each of the two
output paths. The coupler 56 introduces a 90° phase shift
into the coupled portion of the signal, shown as Λ_{e1}^P and
10 Λ_{e2}^P on Figs. 12 and 13, to produce upconverter input signals
5 v_1 and v_2 . For example in Fig. 13, v_1 includes Λ_{e1}^P and Λ_{e2} ,
whereas v_2 includes Λ_{e1} and Λ_{e2}^P . The opposite phase shifts
of v_1 and v_2 results in one of the two electrical signals
being upconverted onto an optical subcarrier frequency $\nu_{o.e.}$.
15 The other electrical signal is upconverted onto the optical
subcarrier frequency $\nu_{o.e.}$ symmetric to the optical carrier
frequency ν_o . A skilled artisan will recognize that
distorted and undistorted optical signals can be produced
20 using the embodiment of Fig. 13 and similar embodiments.

An embodiment of the transmitter 12, shown in Fig. 15,
15 can be also used to provide control over proximate optical
wavelengths by upconverting one or more electrical
25 frequencies onto a plurality of optical carriers provided by
the common optical source 34. The optical carrier lightwave
is split using the optical splitter 60 into split lightwaves
20 carried on a plurality of optical paths $62_1 - 62_n$. A
corresponding plurality of the upconverters 44_{1-n} are
30 disposed along the optical paths. A plurality of electrical
baseband signal $\Lambda_{B1} - \Lambda_{Bn}$ are correspondingly modulated onto
electrical carrier $\nu_{e1} - \nu_{en}$ via modulators 40_{1-n} . The
35 electrical carrier signals $\Lambda_{e1} - \Lambda_{en}$ are provided to the
upconverters 44_{1-n} and converted to subcarrier lightwave
optical signals $\Lambda_{o1} - \Lambda_{on}$ at frequencies $\nu_{oe1} - \nu_{oen}$ and combined
40 using an optical combiner or multiplexer 68. When only one
electrical signal is upconverted onto a split lightwave
30 optical carrier in a path 62_i , single or double sideband
upconverters, with or without carrier suppression, can be
45 used in the invention. Optical filters 58 can be employed
to remove any undesired remnant carrier wavelengths or
mirror image sidebands that are output from the particular
35 modulator used in the transmitter 12.

Fig. 16 shows an embodiment of the transmitter 12 that is configured to transmit four optical signals using a single optical source 34, such as a laser 72, emitting the optical carrier at a central wavelength λ_0 and frequency ν_0 .

The baseband electrical signal $\Lambda_{B1}-\Lambda_{B4}$ are provided as input to corresponding data encoders 50₁₋₄ from an electrical transmission path or from the optical receiver 14 in a short or long reach optical system. The encoded electrical signal is passed through the shaping filter 52₁₋₄ to respective electrical modulators 40. Encoded electrical signals $\Lambda_{C1}-\Lambda_{C2}$ and $\Lambda_{C3}-\Lambda_{C4}$ are modulated onto the electrical carrier at frequency ν_{e1} and ν_{e2} , respectively. The modulated electrical signals $\Lambda_{e11}-\Lambda_{e24}$ are passed through respective signal distorters 32₁₋₄ and electrical amplifiers 54₁₋₄ to provide amplified distorted electrical signals $\Lambda_{e11D}-\Lambda_{e24D}$. Electrical signals Λ_{e11D} and Λ_{e23D} can be routed through electrical coupler 56₁ to upconverter 44₁. Likewise, electrical signals Λ_{e12D} and Λ_{e24D} can be routed through electrical coupler 54₂ to upconverter 44₂. The upconverted optical signals $\Lambda_{oe1D}-\Lambda_{oe4D}$ are combined in the combiner 62 prior to transmission. The interleaving of the electrical frequencies being upconverted allows for the use of optical filters 58, with either single or double sideband modulators, to remove any unwanted sidebands or carrier wavelengths from the optical signals $\Lambda_{oe1D}-\Lambda_{oe4D}$. Transmitters 12 of the present invention can also be used to modulate data onto the lightwave carrier wavelength, in addition to upconverting electrical frequency onto the lightwave.

In the present invention, transmitters 12 configured to provide multiple optical signals, can be further configured to impart opposite polarization to pairs of optical signals being generated by upconverting the electrical signals. For example, the optical combiner 62 in embodiments such as those shown in Figs. 15 and 16 can be a polarizing

5 component, such as a polarizing beam splitter/combiner. The
orthogonal polarization of adjacent signals will reduce or
eliminate nonlinear interaction between the signals, thereby
providing for more closely spaced signal wavelengths and
5 high power signals.

10 Alternatively, as shown in Fig. 17, a separate
polarizing element 74 can be included in the combiner 62.
An embodiment of the polarizing element 74 can include two
oppositely configured polarizing beam splitters 76 connected
15 in series by two parallel paths 78 that produce a
differential travel time between the splitters 76. The
first beam splitter 76 splits the optical signal into two
equal amplitude polarization components. The second beam
20 splitter 76 is used to recombine the two polarization
components. The time differential introduced by the
parallel paths 78 can be established and/or controlled to
introduce differences in the polarization of the channels.
25 For example, optical signals having sufficiently narrow
bandwidths can be introduced to the first beam splitter 76
at a 45° polarization angle to allow optical signal power to
propagate equally in both paths 78. The resulting combined
30 signals emerging from the second splitter 76 would be
orthogonal if the time differential were equal to
 $1/(2 \times \text{frequency difference between the signals})$. Similarly,
25 polarization maintaining fiber can be used in lieu of the
splitters 76 and parallel path 78 to introduce the time
35 differential between the polarization components of a
linearly polarized optical signal.

40 It will be appreciated that the present invention
provides for optical systems having increasing the number of
channels and the transmission performance of optical
systems. Those of ordinary skill in the art will further
appreciate that numerous modifications and variations that
45 can be made to specific aspects of the present invention
35 without departing from the scope of the present invention.
It is intended that the foregoing specification and the
following claims cover such modifications and variations.

Claims

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CLAIMS

5 What is claimed is:

1. An apparatus comprising:

an upconverter having a first upconverter input and a
5 second upconverter input, each input being configured to
10 receive first and second electrical data signals, wherein
the first electrical data signal on the second upconverter
input has a first phase shift from the first electrical data
15 signal on said first upconverter input and the second
10 electrical data signal on the first upconverter input has a
second phase shift relative to the second data signal on the
second upconverter input opposite to the first phase shift
such that said upconverter upconverts the first and second
20 electrical data signals onto corresponding first and second
15 subcarrier frequencies of a lightwave having a carrier
frequency and at least one of the corresponding subcarrier
frequencies is greater than the carrier frequency and at
25 least one of the corresponding subcarrier frequencies is
less than the carrier frequency.

20 2. The apparatus of claim 1, wherein said upconverter
is further configured to suppress signals at the carrier
30 frequency and corresponding mirror image subcarrier
frequencies of the lightwave.

3. The apparatus of claim 1, wherein said upconverter
35 25 includes an electrical coupler having a first output
electrically connected to said first upconverter input and a
second output electrically connected to said second
upconverter input, said coupler being configured to receive
40 the at least first and second electrical data signals and
30 introduce the first phase shift to the first electrical
signal and the second phase shift to the second electrical
signal.

5 4. The apparatus of claim 3, wherein said electrical coupler has a first coupler input for receiving a first electrical data signal at a first electrical frequency and a second coupler input for receiving a second electrical data signal at a second electrical frequency.

10 5. The apparatus of claim 4, wherein said electrical coupler includes a 2x2 3 dB coupler.

15 6. The apparatus of claim 5, wherein the first electrical frequency is equal to the second electrical frequency; and,

20 said first upconverter input receives a portion of the first and second electrical signals that are 90° out of phase with the first and second electrical signals received by the second upconverter input.

25 7. A method of upconverting a plurality of electrical signals onto a lightwave comprising:

30 providing an upconverter configured to upconvert a first electrical signal including at least one electrical frequency carrying information provided to a first upconverter input to a corresponding at least one optical subcarrier frequency greater than a carrier frequency and a second electrical signal including at least one electrical frequency carrying information to a corresponding at least one optical subcarrier frequency less than the carrier frequency;

35 providing first and second electrical signals to the upconverter; and,

40 upconverting the first electrical signals onto subcarrier frequencies greater than the carrier frequency and the second electrical signals onto subcarrier frequencies less than the carrier frequency.

8. The method of claim 7, wherein:

5 said providing an upconverter includes providing an
upconverter having first upconverter input and second
upconverter input and configured to upconvert a plurality of
5 electrical signals onto subcarrier frequencies of a
10 lightwave at the carrier frequency, wherein each electrical
signal is split between the first and second upconverter
inputs and a first phase shift is introduced between the
electrical signals provided to the first upconverter input
15 and the second upconverter input;

10 said providing first and second electrical signal
includes providing a plurality of electrical signals to both
the first and second upconverter inputs, each electrical
20 signal provided to the first upconverter input having the
15 first phase shift relative to the second upconverter input,
and

25 introducing a second phase shift opposite to the first
phase to at least one of the plurality of electrical signals
sufficient to provide for the at least one second phase
20 shifted electrical signals to be upconverted to optical
subcarrier frequencies that are less than a carrier
30 frequency, when the first phase shifted electrical signal
are upconverted to subcarrier frequencies greater than the
carrier frequency and optical subcarrier frequencies that
25 are greater than the carrier frequency, when the first phase
shifted electrical signal are upconverted to subcarrier
35 frequencies less than the carrier frequency; and,

40 said upconverting includes upconverting the plurality
of electrical signals onto subcarrier frequencies of the
30 lightwave.

9. The method of claim 7, wherein said providing an
upconverter includes providing an upconverter configured to
45 suppress the carrier frequency and mirror image subcarrier
frequencies of the lightwave, when upconverting the
35 electrical signals onto the subcarrier frequencies.

5 10. The method of claim 7, wherein said providing first and second electrical signals includes providing first and second electrical signals at the same electrical frequency.

10 5 11. An optical transmission system comprising:
at least one optical receiver configured to receive an optical data signal; and,
at least one optical transmitter configured to transmit the optical signal to said at least one optical receiver via
15 10 optical fiber, said at least one transmitter including
an upconverter having a first upconverter input and a second upconverter input, each input configured to receive
20 20 at least first and second electrical data signals, said upconverter being configured to upconvert the at least first
15 15 and second electrical data signals onto corresponding at least first and second subcarrier frequencies of a lightwave
25 25 having a carrier frequency to produce the optical signal, wherein at least one of the corresponding subcarrier
20 20 frequencies is greater than the carrier frequency and at least one of the corresponding subcarrier frequencies is
30 30 less than the carrier frequency.

 12. The system of claim 11, further comprising:
an electrical carrier source configured to provide first and second electrical carriers at the same frequency;
35 25 a first electrical modulator configured to modulate a first baseband signal onto the first electrical carrier to produce the first electrical data signal; and,
40 40 a second electrical modulator configured to modulate a second baseband signal onto the second electrical carrier to
30 30 produce the second electrical data signal.

13. The system of claim 11, further comprising:

5 a first signal distorters configured to distort the first electrical data signal to compensate for chromatic dispersion of the optical data signal carrying data from the first electrical data signal; and,

10 a second signal distorters configured to distort the second electrical data signal to compensate for chromatic dispersion of an optical data signal carrying data from the second electrical data signal.

15 14. The apparatus of claim 13, further comprising:

20 a data encoder configured to encode and synchronize with a clock signal at least one of the electrical data signals and provide an encoded data signal; and,

25 a low pass shaping filter configured to shape the encoded electrical data signal, wherein, said signal distorter is further configured to separate the encoded electrical data signal into in-phase and quadrature phase components;

30 an electrical carrier source configured to provide an electrical carrier; and,

35 an IQ electrical modulator configured to modulate the in-phase and quadrature components of the electrical signal onto the electrical carrier and provide a distorted modulated electrical carrier to said optical upconverter, wherein said optical upconverter is configured to upconvert the distorted modulated electrical carrier onto the lightwave at a subcarrier frequency.

40 15. The apparatus of claim 13, wherein said signal distorter includes a group delay equalizer.

45 16. The system of claim 11, further comprising a polarizing element configured to orthogonally polarize the first subcarrier frequency relative to the second subcarrier frequency.

5 17. The system of claim 11, further comprising:
 an optical splitter configured to split the lightwave
into a plurality of split lightwaves at the carrier
frequency;

10 5 a plurality of said upconverters corresponding to the
split lightwaves and configured to impart electrical data
signals carrying information onto the split lightwaves at
different optical frequencies; and,

15 10 an optical combiner configured to recombine the split
lightwaves into an optical data signal carrying the
information on the different optical frequencies.

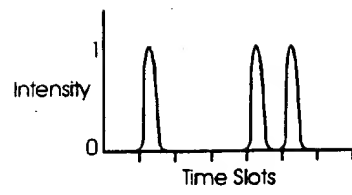


Fig. 1a

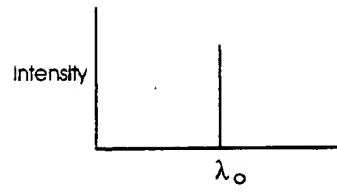


Fig. 2a

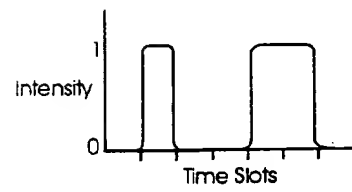


Fig. 1b

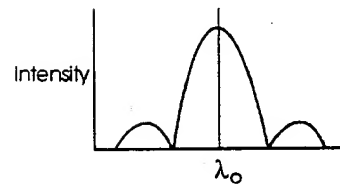


Fig. 2b

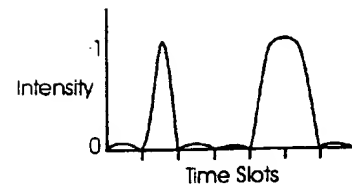


Fig. 1c

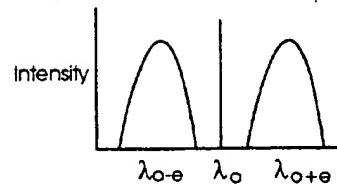


Fig. 2c

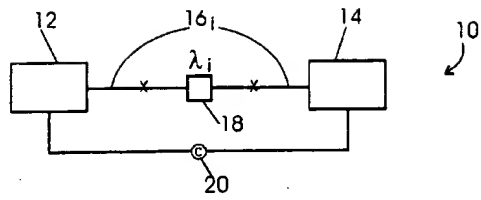


Fig. 3

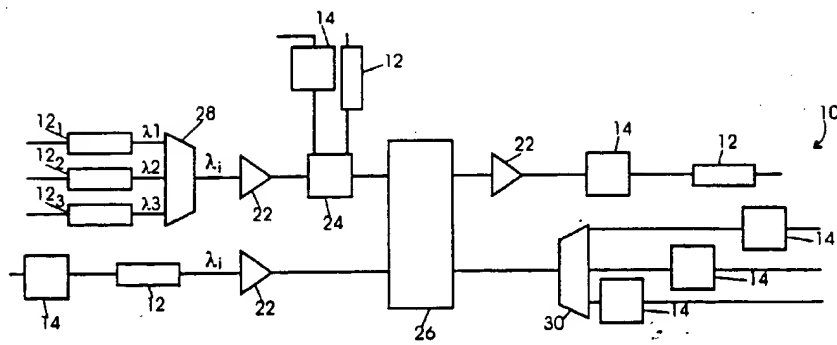


Fig. 4

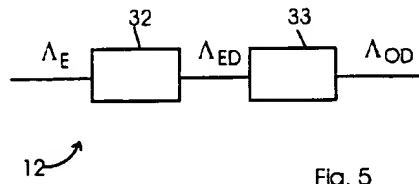


Fig. 5

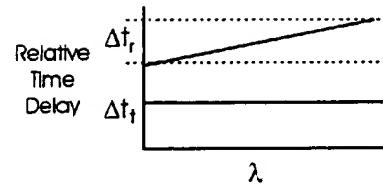


Fig. 6a

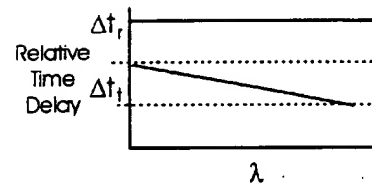


Fig. 6b

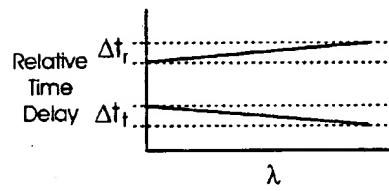
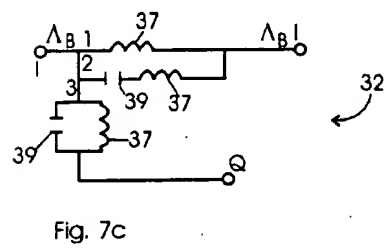
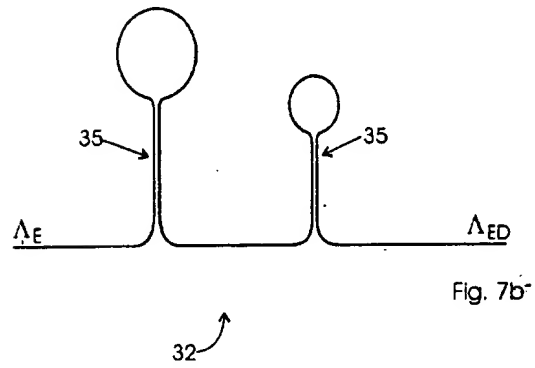
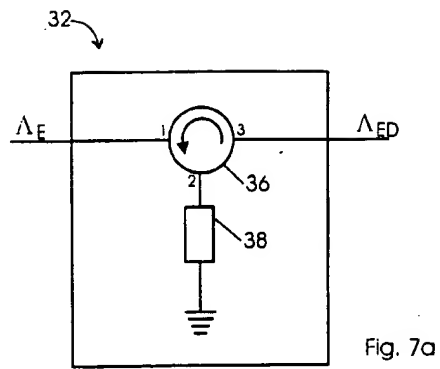
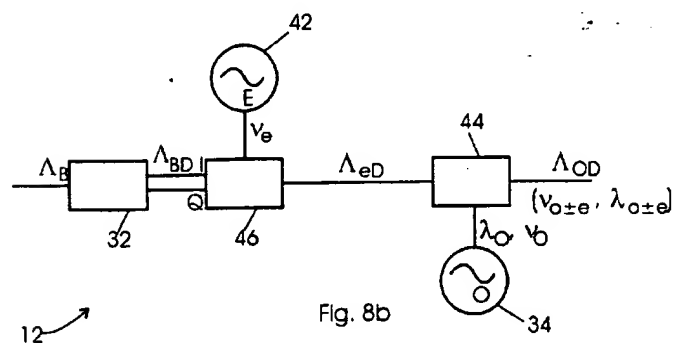
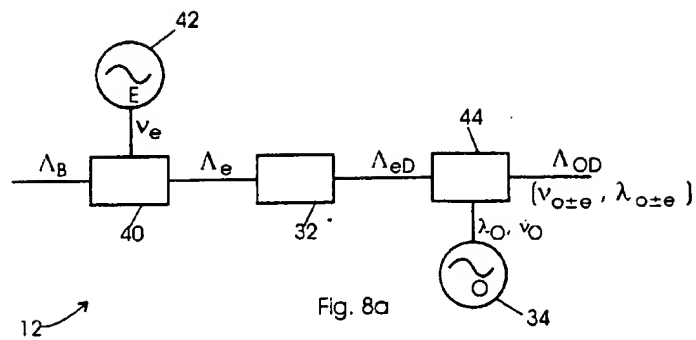
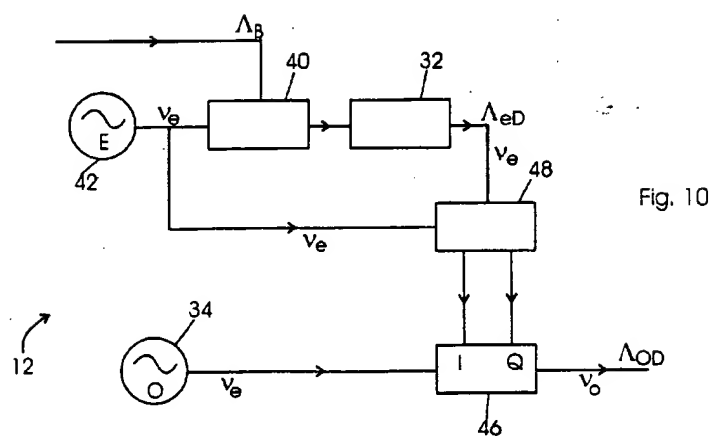
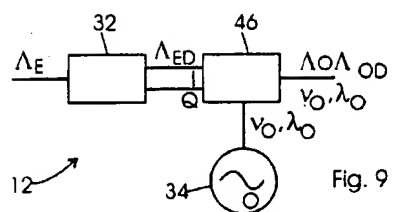


Fig. 6c







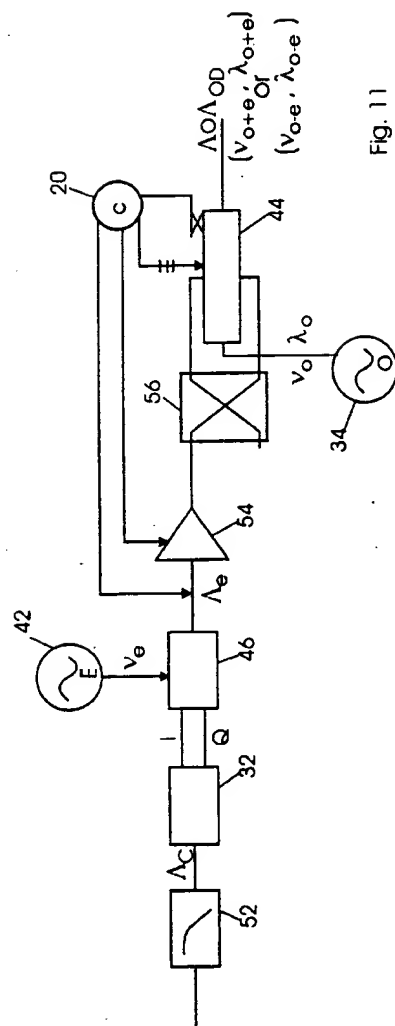


Fig. 11

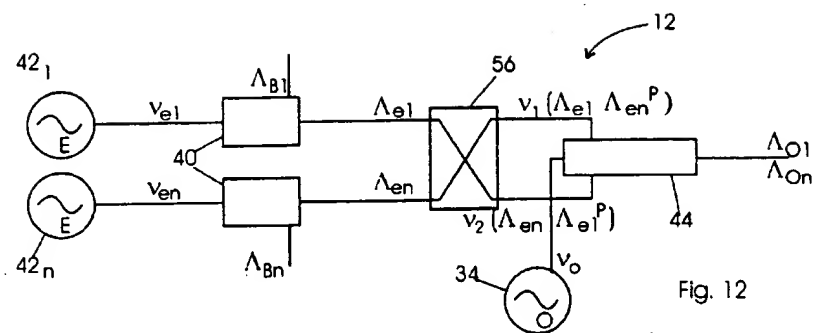


Fig. 12

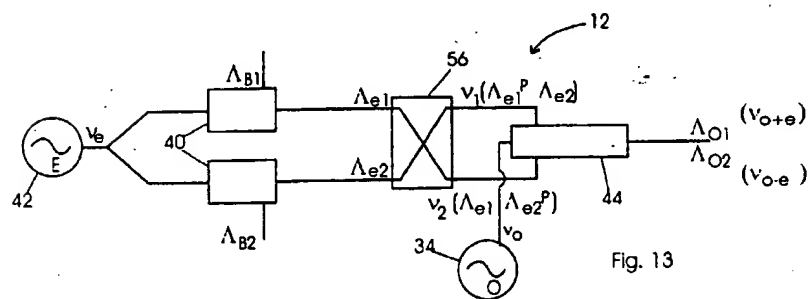
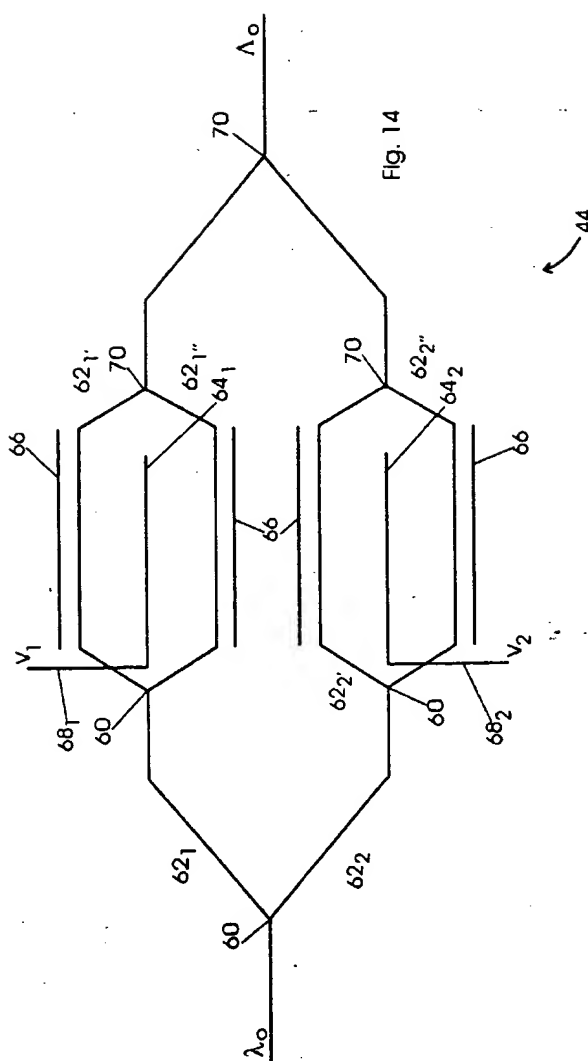


Fig. 13



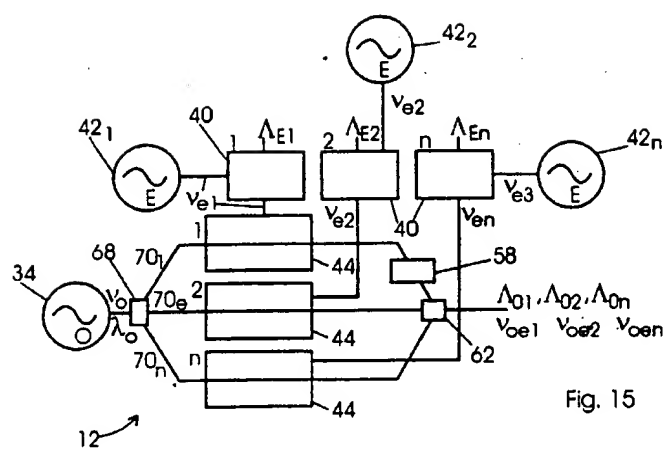


Fig. 15

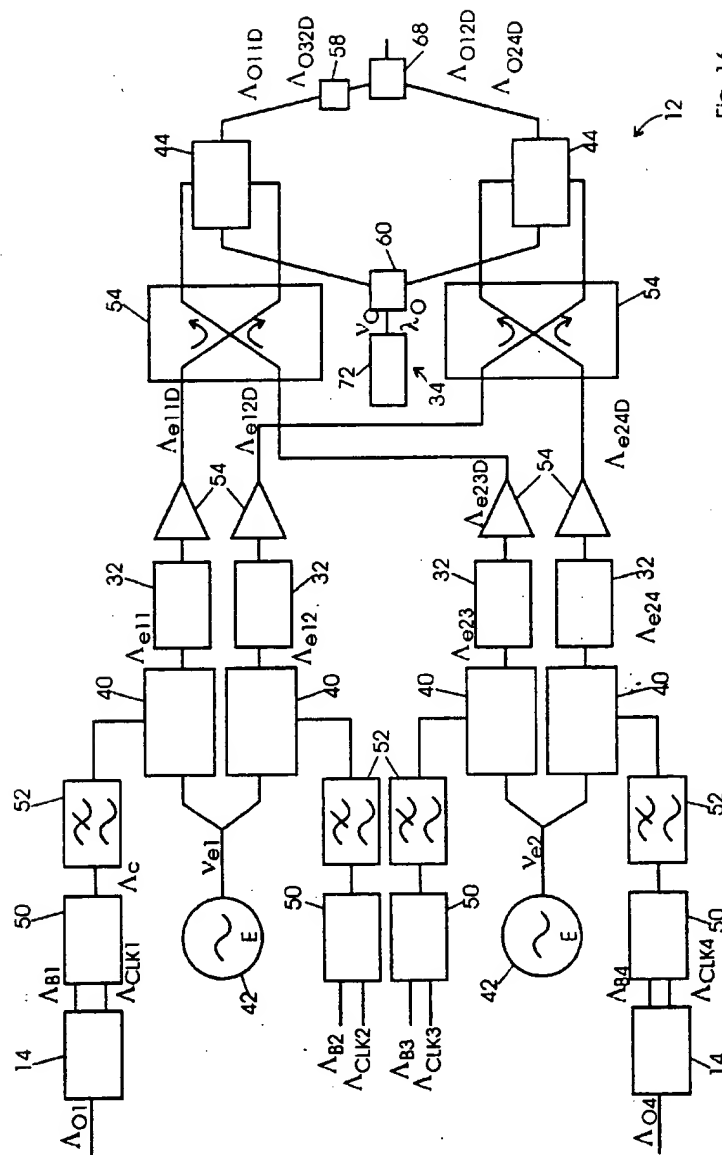


Fig. 16

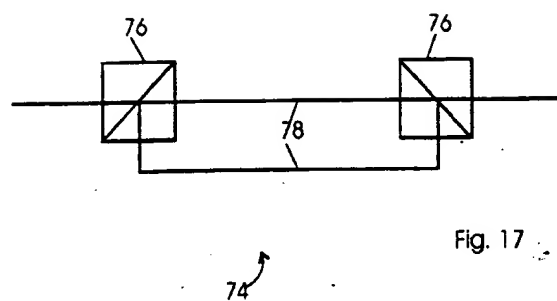


Fig. 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/25885**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(6) : IPC(6): H04B 10/04, 10/16; G02B 6/10

US CL : US: 359/181, 188; 385/3

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : US: 359/181, 188; 385/3

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONEElectronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EAST, WEST**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A, E	US 5,917,638 A (FRANCK et al) 29 June 1999, Fig. 16, col. 4, lines 32-67, col. 6, lines 56-67.	1-17
A	US 5,239,401 A (OLSHANSKY) 24 August 1993, Fig. 5, col. 6, lines 22-67, col. 7, lines 1-67.	1-17
A	US 5,101,450 A (OLSHANSKY) 31 March 1992, Fig. 5, lines 6, lines 44-67, col. 7, lines 1-67.	1-17
A	US 5,543,952 A (YONENAGA et al) 06 August 1996, Fig. 5, col. 5, lines 52-67, col. 6, lines 1-67.	1-17

☐ Further documents are listed in the continuation of Box C.
 ☐ See patent family annex.

* Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" documents defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E" earlier documents published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L" document which may throw doubt on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"A"	document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means		
"P" document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search

16 FEBRUARY 2000

Date of mailing of the international search report

02 MAR 2000

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